Holographic Optical Element Raman Lidar

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Introduction

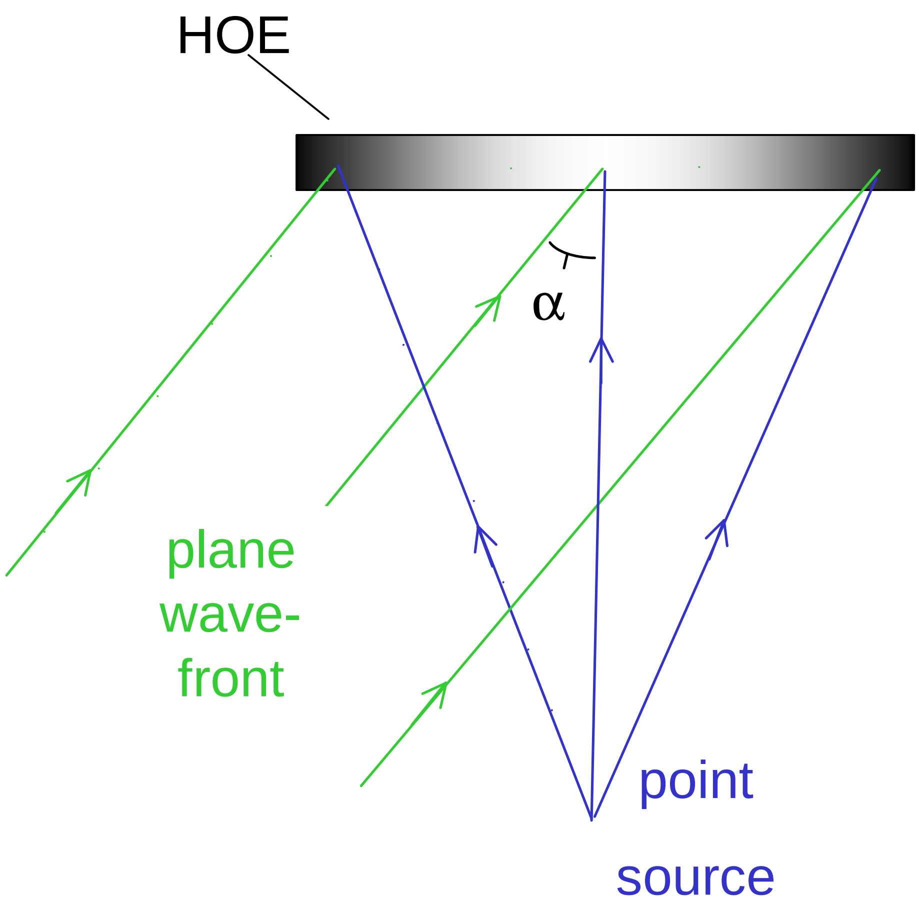
- Although cross-sections are considerably smaller than in Rayleigh scattering, Raman signal detection offers a significant multiplexing advantage in that a fixed, single-wavelength source yields spectroscopic information on a wide variety of molecular species.

- Holographic optical elements (HOEs) have been used by Schwemmer and Guerra to dramatically reduce the size and weight of beam scanning lidar systems by combining the telescope and steering mirror functions into a single plate.

- So far, only elastic-scattering HOE lidars have been demonstrated; however, HOEs inherently exhibit wavelength dispersion due to diffraction, thus spectral information due to inelastic processes (such as Raman scattering) can be retrieved.

- In this demonstration, a single HOE is used to simultaneously perform the function of a telescope and spectrometer and record Raman-shifted backscatter in an experimental lidar system.

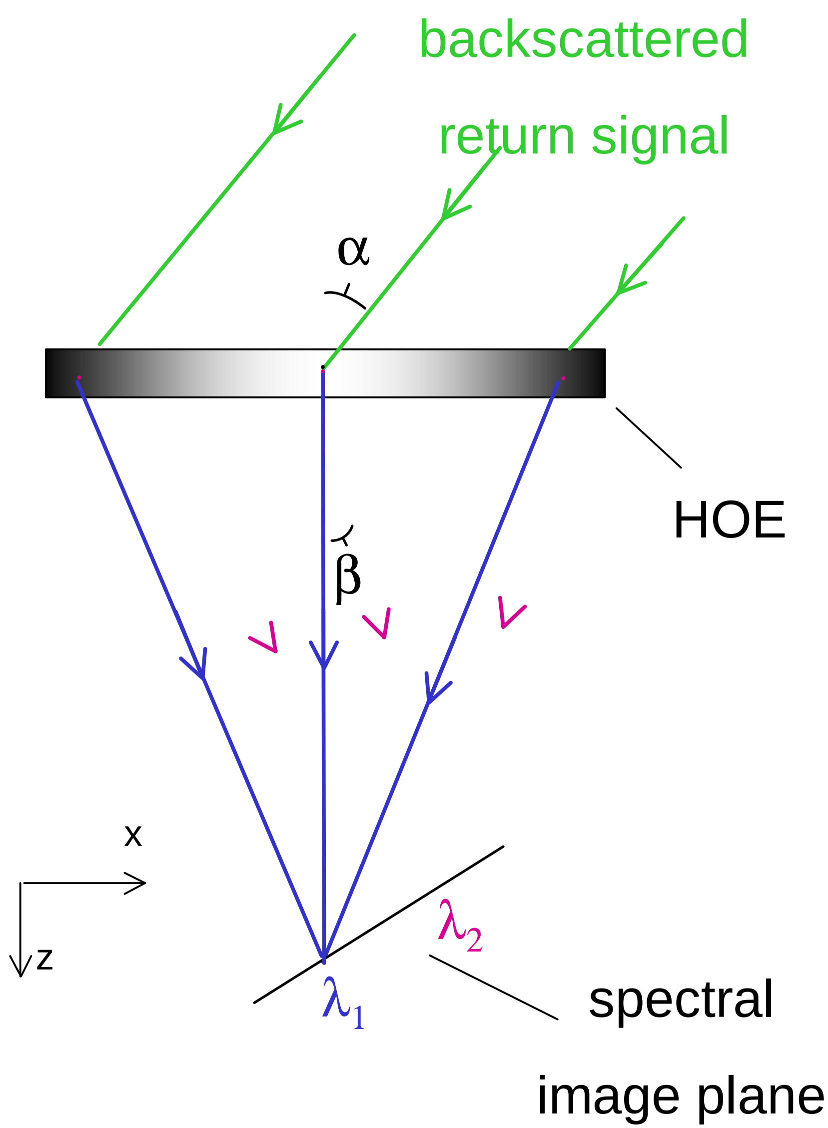
HOE exposure set-up



- A HOE with focusing properties is fabricated by recording the interference between a collimated reference beam (green) at angle α, and an on-axis spherical wave front (blue) as shown.

- By chemical processing, a refractive index modulation within the holographic film can then be obtained that corresponds to the recorded interference pattern.

Raman HOE Receiver



- For lidar measurements, the conjugate beam (green) represents the atmospheric back-scatter return signal induced by an outgoing pulse of laser radiation.

- The reconstructed beam on the opposite side of the HOE (blue) is brought to a focus.

- Due to diffraction, wavelength-shifted light due to Raman scattering (purple) appears at a different position along the spectral image plane.

Image along z axis (focal length) can be approximated by

$$z = \frac{h}{l}$$

where η = focusing power constant
λ = wavelength

Image position in x axis (lateral displacement) is given by the Bragg formula

$$m\ l = b(\mathrm{Sin}\ a \pm \mathrm{Sin}\ b)$$

where m = 1 (diffraction order); b = grating spacing; α = input angle to HOE; β = output angle from HOE

Assuming small angle approximation (Sinβ = x/z), the combination of focal length (z) and (x) lateral displacement from the optical axis can be represented by the following coordinate system

$$\overset{\mathrm{r}}{P} = \begin{pmatrix} z \\ x \end{pmatrix} = \frac{h}{l}\begin{pmatrix} 1 \\ \frac{l}{b} - Sin a \end{pmatrix}$$

For a fixed angle α, a change to longer wavelengths results in a diagonal movement of focus position closer to the HOE.

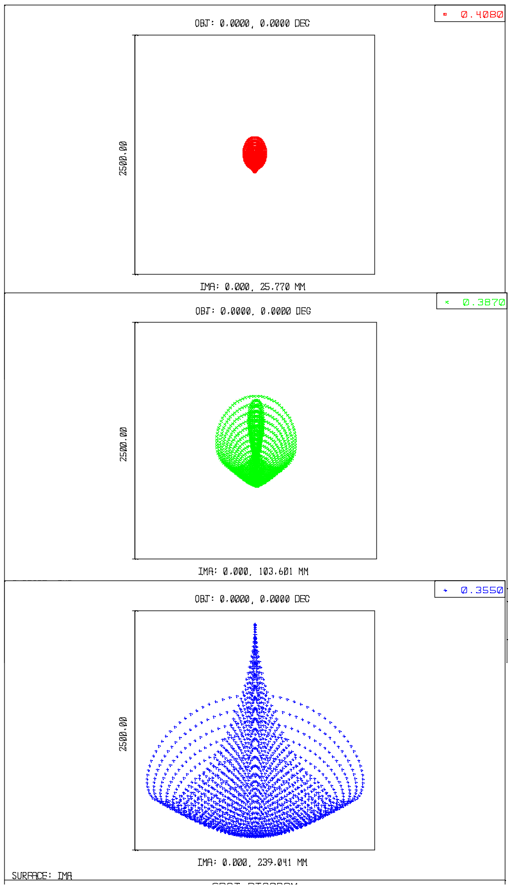
Raman HOE Design & Fabrication

Raytrace Spot Diagrams

408 nm

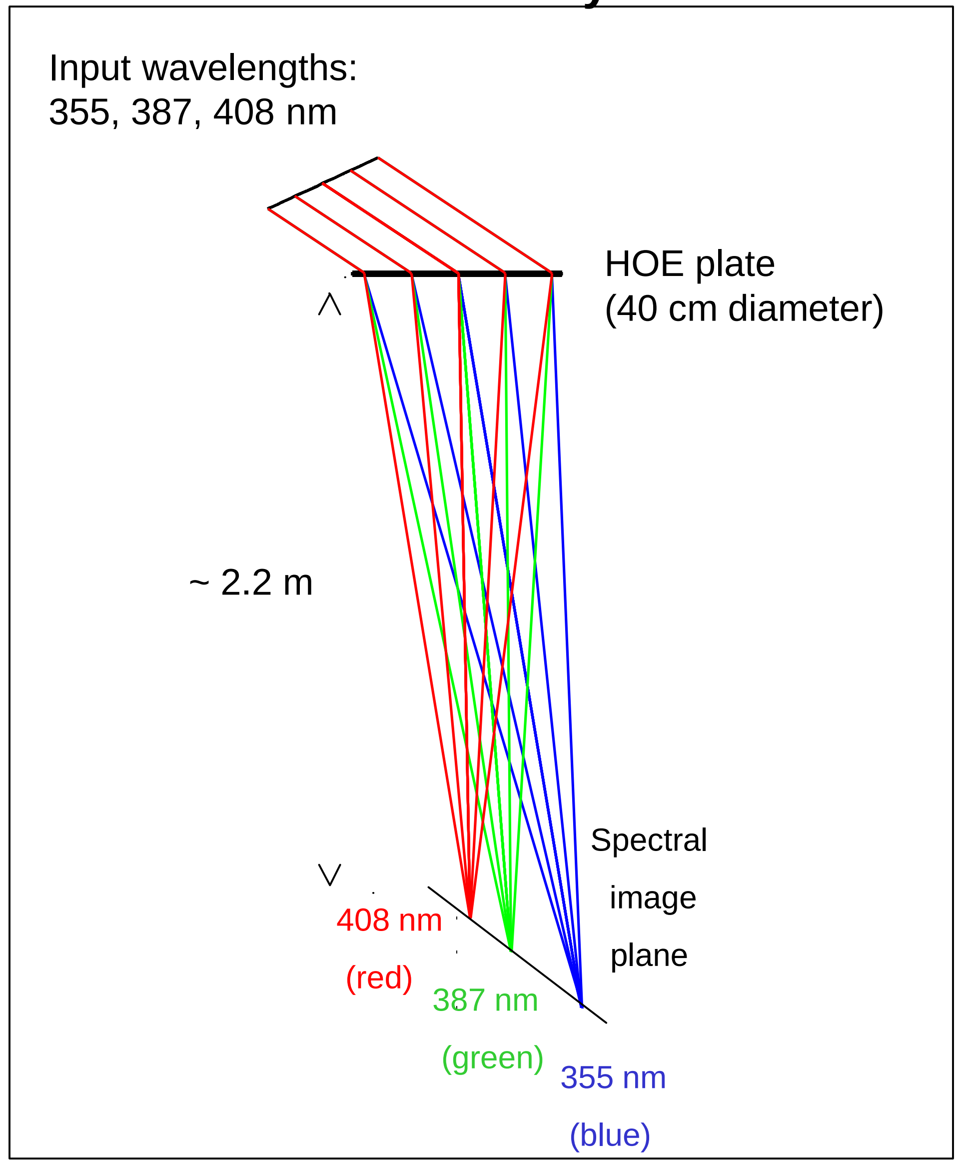
387 nm

355 nm



Spot sizes increase off axis

Geometrical Ray Trace



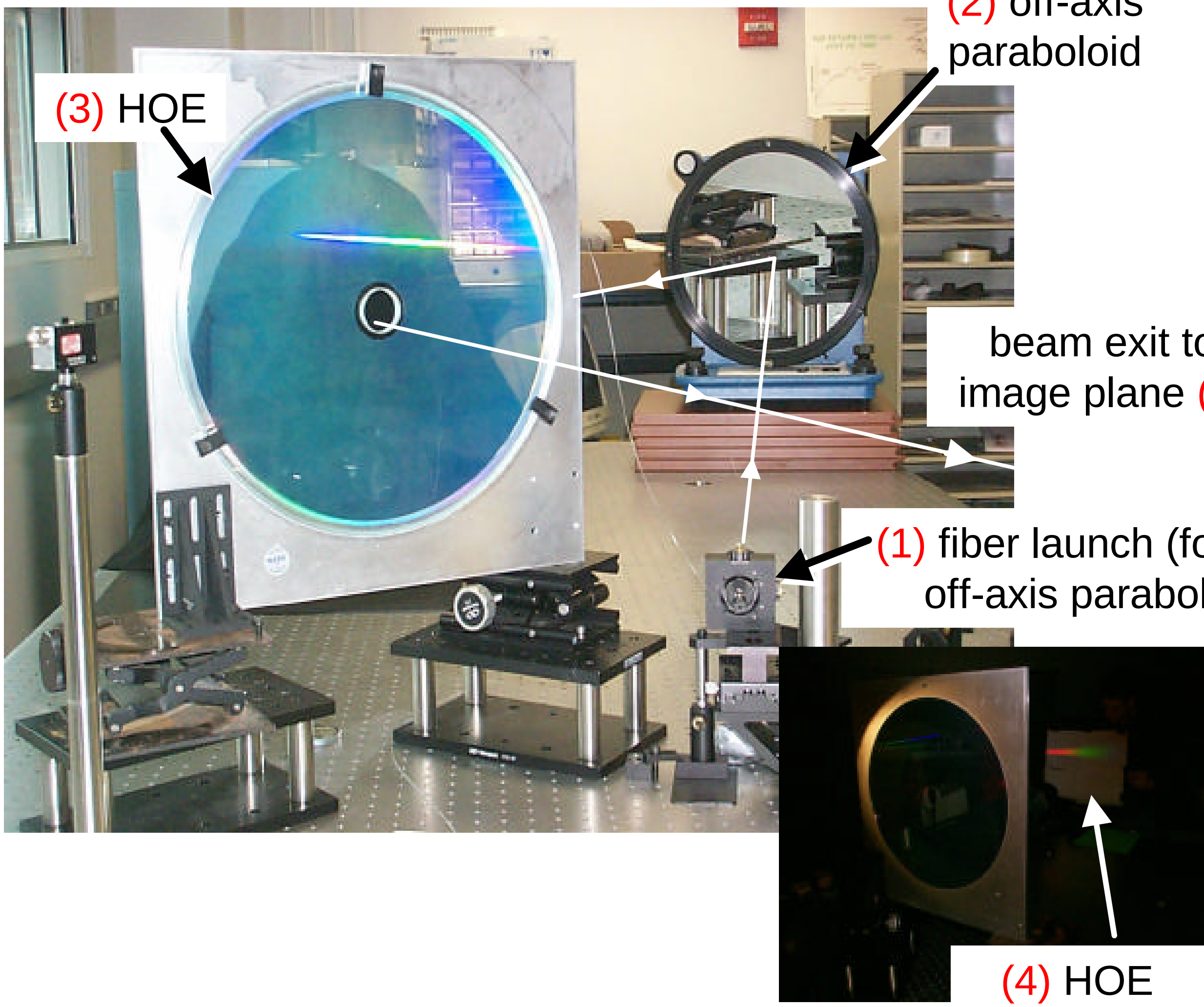
- Large diameter (40 cm) HOE plates were designed and fabricated by Rallison at Ralcon Development Labs.

- Geometrical raytrace studies and numerical analysis indicate that good focus spot sizes and high diffraction efficiency could be obtained over 355-408 nm.

- In addition to elastic scattering, this wavelength range covers Raman-shifted spectra from N_2, O_2, H_2O vapor, H_2O liquid, NO_2, SO_2, CH_4, and CO_2 when using a frequency tripled Nd:YAG laser source.

Raman HOE Characterization

Laboratory Set-up

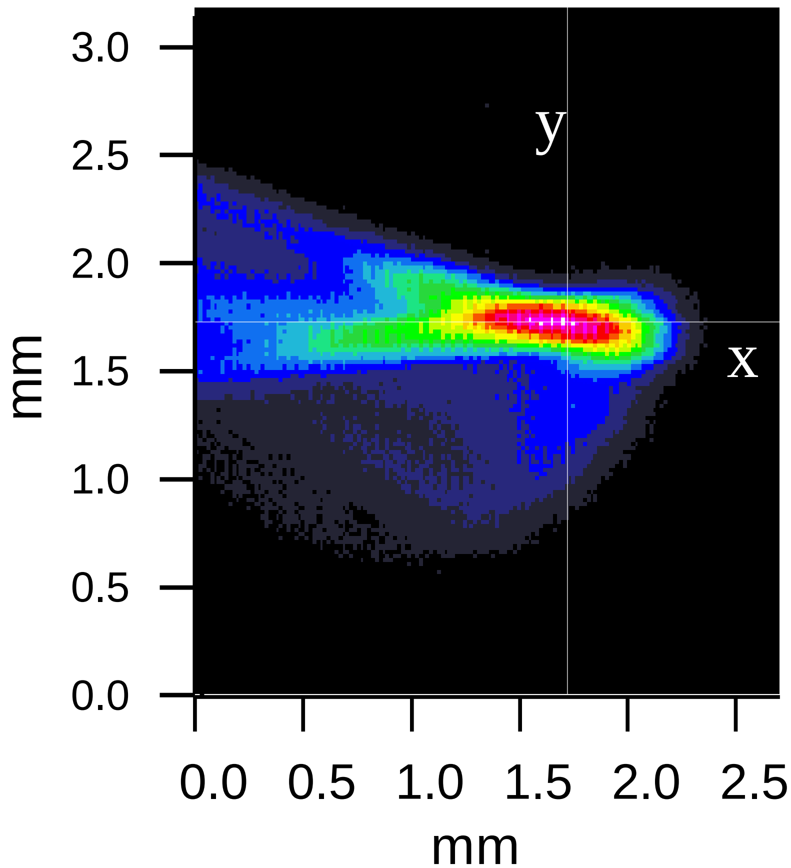


- Spectral performance of two different HOE plates were evaluated over the 355-408 nm wavelength using light generated by a high pressure xenon arc lamp that was spectrally narrowed to 0.2 nm using a monochromator.

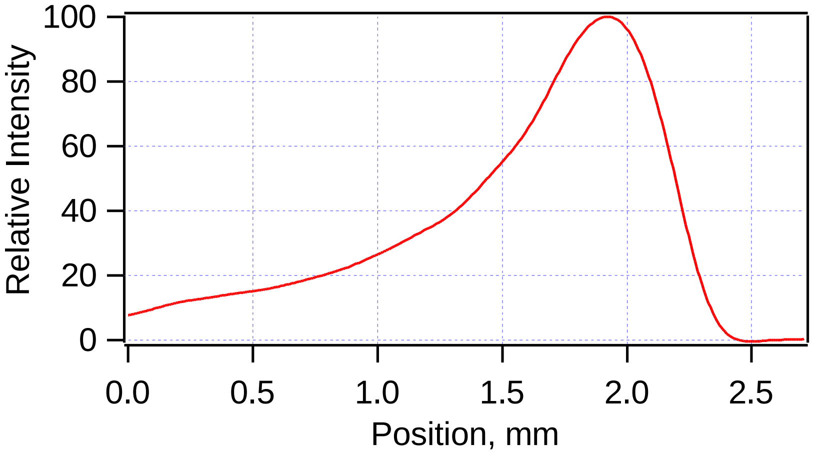
- Multi-mode fiber was used to guide the light from the monochromator to the focus point (1) of an off-axis parabolic mirror (2) to generate a 40 cm diameter collimated beam to enable full-aperture illumination of the HOE (3).

- Spot size measurements and efficiency at different wavelengths were recorded at the image plane (4).

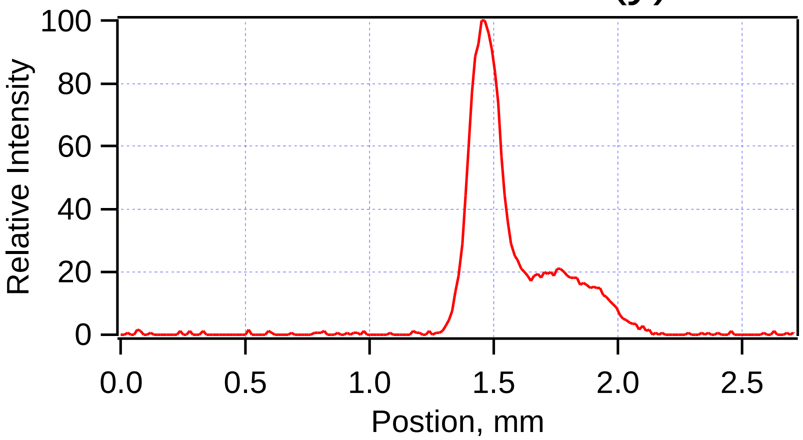
Example Spot Size measurement (408 nm, 33 deg.)



Horizontal Profile (x)



Vertical Profile (y)



Raman HOE Image Plane Characteristics

<u>Focal Length (mm)</u>

Wavelength	*Ray Trace*	*Measured*
355 nm	2555	2594
387 nm	2337	2362
408 nm	2205	2237

<u>Focus Spot Sizes (mm)</u>

Wavelength	*Ray trace*	*Measured*	
		*(Horiz)**	*(Vert)*
355 nm	1.2	2.5	1.5
387 nm	0.4	1.5	0.62
408 nm	0.1	1.5	0.59

*Horizontal width has contribution from spectral bandwidth of source (est. ~ 0.2 nm)

- Spot sizes correspond to < 0.5 nm resolution (FOV < 0.6 mad)
- Maximum first order diffraction efficiency at 355, 387, & 408 nm ranged from 60-65% at 35 deg. angle of incidence.
- Correction optics can be used to improve spot size, but were not implemented for this initial demonstration

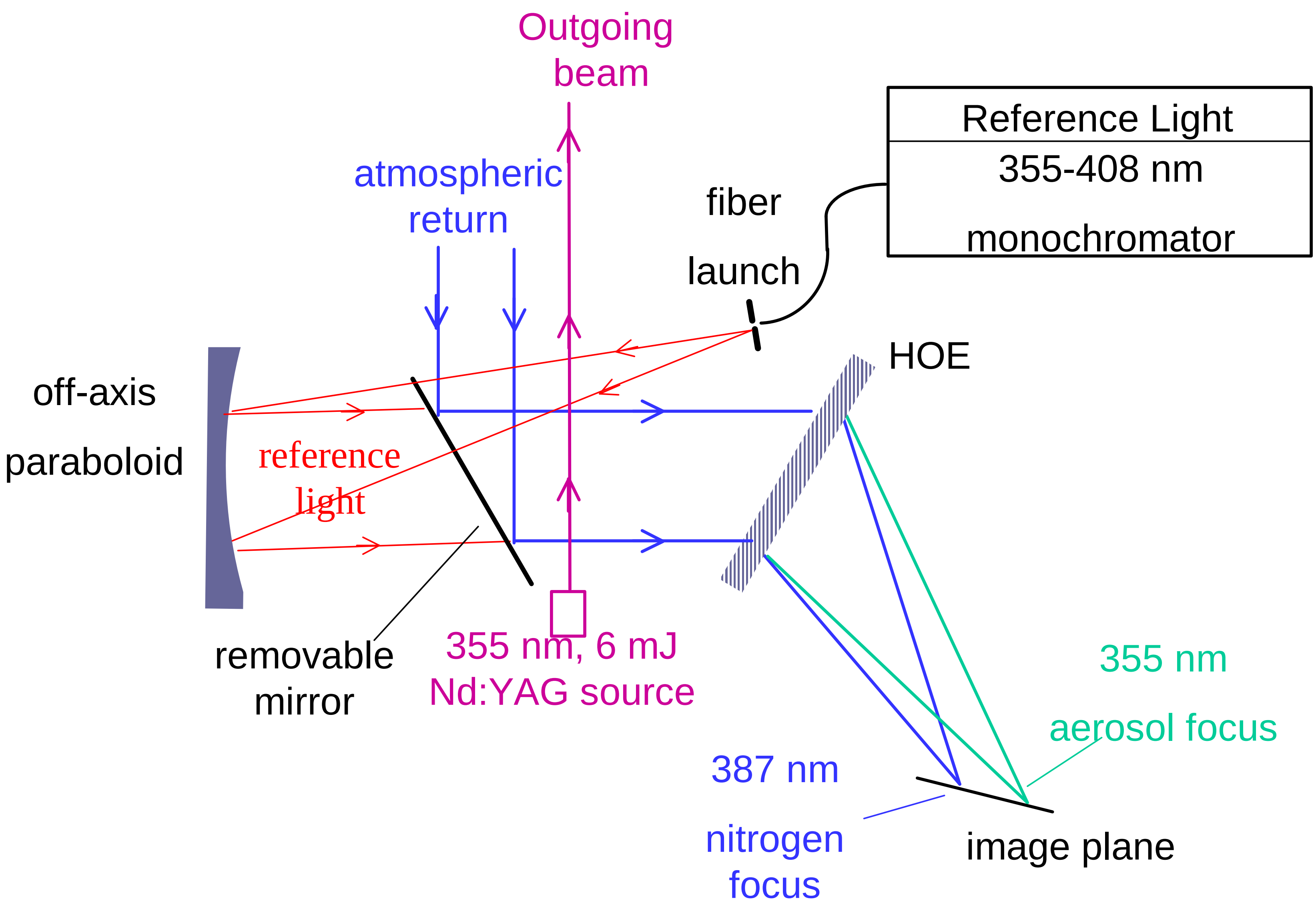
HOE Raman Lidar Experiment

- To demonstrate the measurement of atmospheric profiles of wavelength-shifted light due to Raman scattering, the experimental system shown (to the right) was constructed.

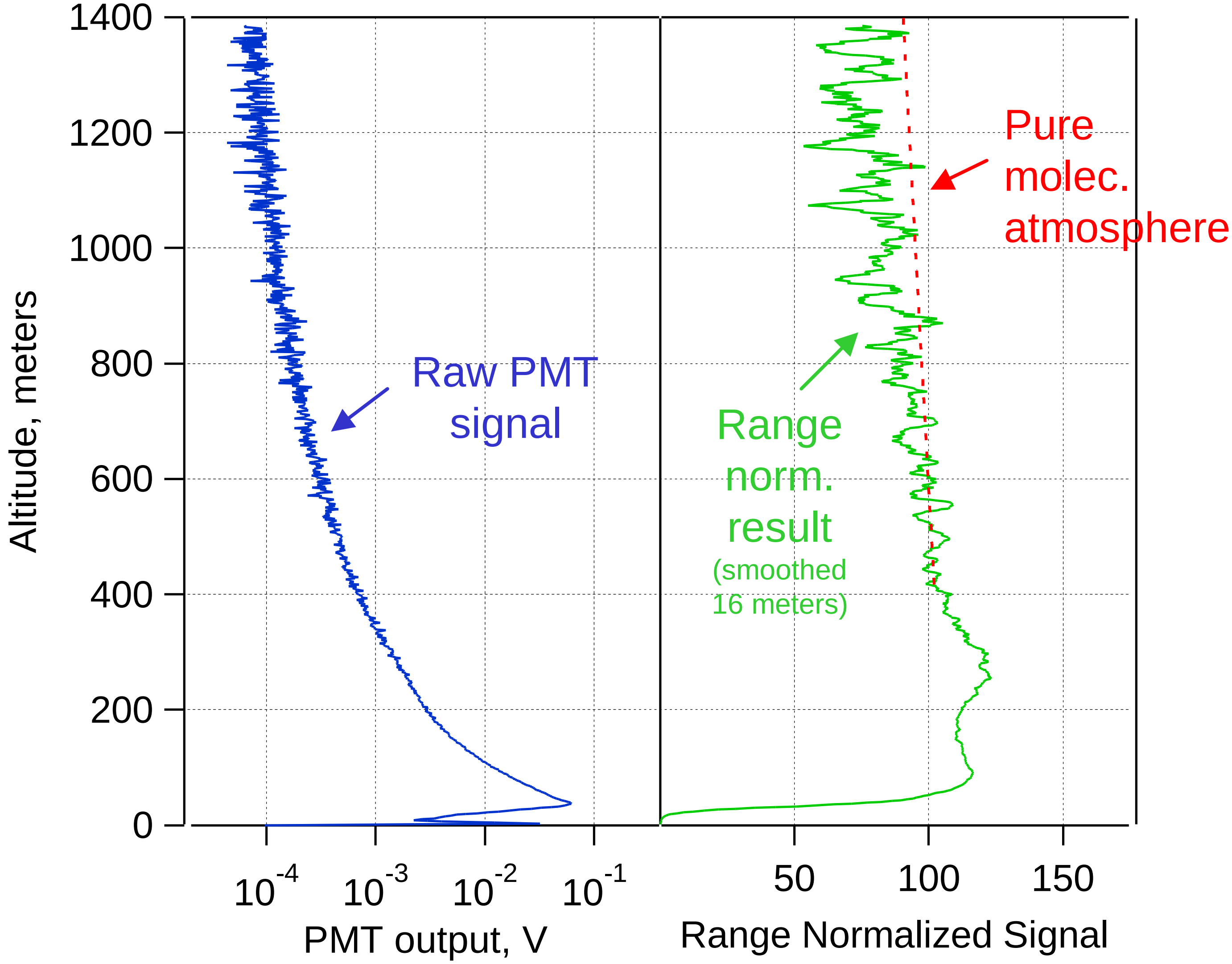
- A 6 mJ/pulse, 30 Hz Nd:YAG source was directed vertically into the atmosphere. Scattered return light was reflected by a flat turn mirror to the HOE mounted at 35 deg. angle of incidence. System included reference light path using monochromator source to establish image wavelength location prior to atmospheric measurements.

- For this initial demonstration, Raman backscatter for atmospheric nitrogen at 387 nm was examined since it has a well-known cross-section, its signal is relatively strong, and its atmospheric density profile is stable.

Experimental Set-up



Measurement of Atmospheric Nitrogen



- Results were obtained at night using a photomultiplier tube placed at the 387 nm focus position and filtering the light with a bandpass filter that provided > 10^{-10} out-of-band rejection to prevent stray scattered radiation (at 355 nm) from saturating the PMT.

- The raw PMT signal is shown on the left graph (blue trace), shows the characteristic decay shape associated with atmospheric N_2.

- The background subtracted, range-squared normalized result is shown on the right (green trace), smoothed to 16 meter vertical resolution and corrected for standard atmospheric transmission.

- Above 400 meters, the signal decreases at a stable rate slightly faster than expected for a pure molecular atmosphere (red dashed line). This difference is attributed to the presence of boundary layer aerosols.

- Random noise in the 1-1.4 km range corresponds to ~ 10% rms of the signal for a 26 second time-average at 16 meter resolution.

Summary

- A new method for retrieval of Raman lidar measurements using a single holographic element (HOE) to simultaneously perform the function of a telescope and spectrometer has been described.

- HOEs fabricated for this work exhibited spectral resolution of < 0.5 nm in the wavelength range from 355-408 nm which is suitable to retrieve Raman-shifted spectra from frequency-tripled Nd:YAG laser source.

- Using this technique, Raman scattering from atmospheric nitrogen from near the surface to ranges above 1 km has been observed at night using a low power laser source.

- This approach has the unique advantage of being able to recover a wide range of Raman-shifted wavelengths using a simple receiver geometry.

Acknowledgements

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References

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